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Prepared by:
Training Group.

Authorised by:
Superintending Engineer,
Operations Planning and Programming Branch, HQ.

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Engineering Training Group, 6 Flinders Street, Melbourne, Victoria, 3000

TRANSFORMERS AND INDUCTORS

(PREVIOUSLY RGP 089)

1. INTRODUCTION.

1.1 A transformer is a device for transferring electrical energy from one A.C. circuit to another by means of a common magnetic circuit.

1.2 Transformers are used in all branches of electrical engineering but we are concerned only with those used in telecom equipment. These range from very large iron cored units in low frequency power plant, to very small air cored transformers in high frequency radio applications.

Modern transformers are extremely efficient and reliable, and very rarely need replacement. Because of this, their importance is often overlooked, and the reasons for their inclusion in a circuit are not always completely understood.

1.3 The basic theory of transformer operation is outlined in the "Electromagnetic Induction" paper of Applied Electricity 1, and this should be revised before proceeding further.

This paper deals further with the theory of operation of transformers, and gives additional information on their construction and use.

2. TRANSFORMER THEORY.

2.1 In the paper "Electromagnetic Induction" of Applied Electricity 1, we saw that a transformer consists of two insulated windings, called Primary and Secondary, arranged on a core of iron or other suitable material, so that the windings are magnetically coupled.

When an alternating voltage is applied to the primary winding, a flux is set up in the core which changes at the same rate as the primary current. This flux links the turns of both windings and according to Lenz's and Faraday's Laws, produces

- a self induced e.m.f. in the primary winding;
- a mutually induced e.m.f. in the secondary winding.

As both e.m.f's are produced by the same flux, the rate of change of flux is the same for each turn in the primary and secondary windings. Therefore, the induced e.m.f. per turn is the same in each winding.

When both windings have the same number of turns the self induced e.m.f. in the primary winding is equal to the mutually induced e.m.f. in the secondary winding.

When the secondary winding has twice as many turns as the primary winding, the induced e.m.f. in the secondary winding is twice the value of the induced e.m.f. in the primary winding.

As the self induced e.m.f. in the primary winding can be considered to be equal to the applied primary voltage, the ratio of the primary voltage (E_p) to the induced secondary voltage (E_s) is equal to the ratio of the number of primary turns (N_p) to the number of secondary turns (N_s).

That is -

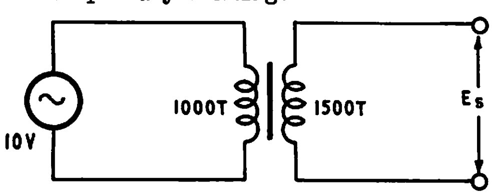
$$\frac{E_p}{E_s} = \frac{N_p}{N_s} \quad \text{or} \quad E_s = E_p \times \frac{N_s}{N_p}$$

As the ratio of secondary turns to primary turns $(\frac{N_s}{N_p})$ is the Turns Ratio (T), the secondary voltage can be found from -

$$E_S = T \times E_P$$

where
E_s = Secondary voltage
E_p = Primary voltage
T = Ratio of secondary turns to primary turns.

Example No. 1. A transformer has 1000 turns on the primary winding and 1500 turns on the secondary winding. Find the secondary voltage when an alternating voltage of 10 volts is applied to the primary winding.



$$T = \frac{N_s}{N_p}$$
$$= \frac{1500}{1000} = \frac{1.5}{1}$$

$$E_s = T \times E_p$$
$$= \frac{1.5 \times 10}{1} = \underline{15 \text{ volts.}}$$

Answer = 15 volts.

2.2 A transformer is essentially a connecting device by means of which energy is transferred from an energy source to a load circuit.

Within the transformer, voltage transformation may occur, but it must always be remembered that any increase or decrease in the power output from the secondary winding must be accompanied by a corresponding increase or decrease in power input to the primary winding.

The action of transformers can best be shown by vector diagrams which depict the operating conditions in the primary circuit for different types of secondary load circuits.

For our purposes, it is sufficient to consider the action of a perfect transformer, that is, one which has no power losses. Such a device is, of course, only theoretically possible, as in all practical transformers, energy is dissipated in the resistance of the windings and in eddy currents and hysteresis effects in the core. However, as correctly designed transformers can be up to 98% efficient, these losses have only a minor effect on the principles of operation and can be overlooked at this stage.

2.3 No-Load Conditions. When the secondary winding of a transformer is left with an "open" circuit, no transfer of energy can take place between windings, and thus the primary winding is a purely inductive circuit with a comparatively high value of inductance. When an alternating voltage is applied to the primary winding (Fig. 1a), the inductive reactance of the primary winding limits the current to a small value.

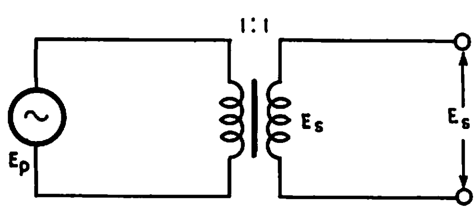
This current is called the magnetising current, as it establishes the flux in the core. Because of the inductance of the primary winding, this current lags the applied primary voltage by 90°.

These "no-load" conditions in the primary circuit are shown vectorially in Fig. 1b, in which

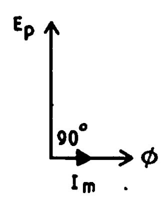
- the flux vector (ϕ) is drawn horizontally as a reference;
- the magnestising current vector (I_m) is drawn in phase with flux;
- the primary voltage (E_p) is drawn so that I_m lags by 90°.

The flux links the turns of the secondary winding, and induces an e.m.f. (E_s) which, according to Lenz's Law, is 180° out of phase with E_p. For simplicity, it is assumed that the transformer has an equal number of turns on each winding and therefore E_s can be drawn equal to, but 180° out of phase with E_p (Fig. 1c).

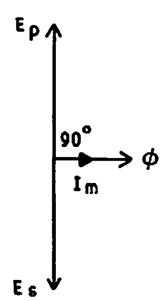
Under no-load conditions, therefore, an e.m.f. is induced in the secondary winding, but as the power requirements of the secondary circuit are zero, only a small magnetising current flows in the primary winding, lagging the primary voltage by 90°.



(a)



(b)



(c)

FIG. 1. TRANSFORMER WITH NO SECONDARY LOAD.

2.4 Loaded Conditions. When a load circuit is connected to the secondary winding, energy is transferred from the primary source to the secondary circuit, where it is dissipated in the secondary load.

As the no-load primary current is "wattless", that is, it lags by 90°, additional current must flow in the primary circuit, so that energy is available for transfer to the secondary circuit. This increase in primary current is brought about as follows:-

When current flows in the secondary winding it tends to set up a flux in the core. According to Lenz's Law, this flux opposes that produced by the primary current, and therefore it reduces the flux producing properties, or inductance of the primary winding.

With less inductance, the inductive reactance of the primary winding is reduced and the current in the primary winding increases.

The additional current in the primary winding is called the "Balance current", as it counteracts or balances the demagnetising effect of the secondary current. Irrespective of the type of circuit connected to the secondary winding, the magnetising effect of the balance current is always equal and opposite to the demagnetising effect of the secondary current, or

- balance current (I_b) is always 180° out of phase with secondary current (I_s);
- balance current ampere-turns ($I_b \times N_p$) equals secondary current ampere-turns ($I_s \times N_s$).

Therefore

$$I_b = T \times I_s$$

where

I_b = Primary balance current
I_s = Secondary current
T = Turns Ratio. $(\frac{N_s}{N_p})$

2.5 Transformer with Resistive Secondary Load. Fig. 2a shows a transformer which has an equal number of turns on each winding. The action of the transformer when a resistive load is connected to the secondary winding is shown in Figs. 2b, c and d.

Fig. 2b shows the vector diagram for the no-load condition. This is the starting point for all transformer vector diagrams.

As the secondary load is resistive, the secondary current (I_s) is in phase with the secondary voltage. (Fig. 2c.) To overcome the demagnetising effect of I_s, a balance current (I_b) flows in the primary winding, 180° out of phase with I_s. As the windings have an equal number of turns, I_b is equal to I_s (Fig. 2c).

In Fig. 2d, the total primary current (I_p) is found from the vector sum of I_m and I_b. It can be seen that the primary current under load is much greater than the no-load primary current, and that the phase angle of the primary circuit is much less than 90°. This indicates that the energy dissipated in the resistive load circuit is being supplied by the primary voltage source.

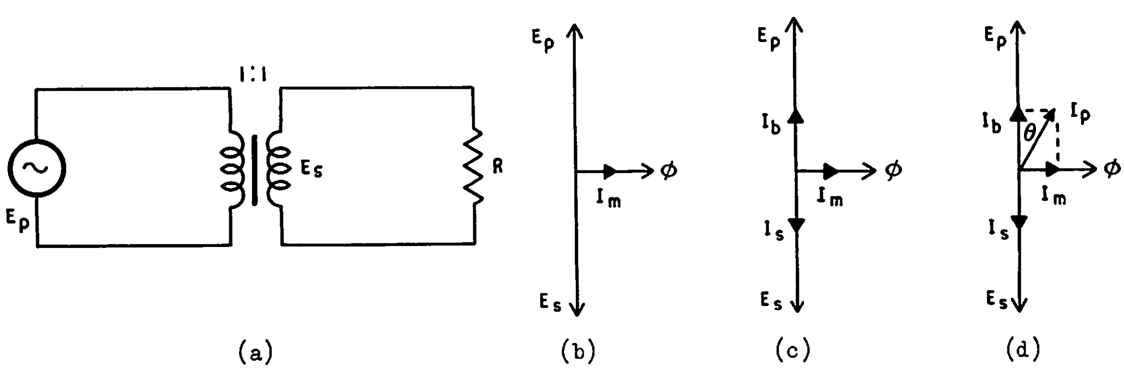
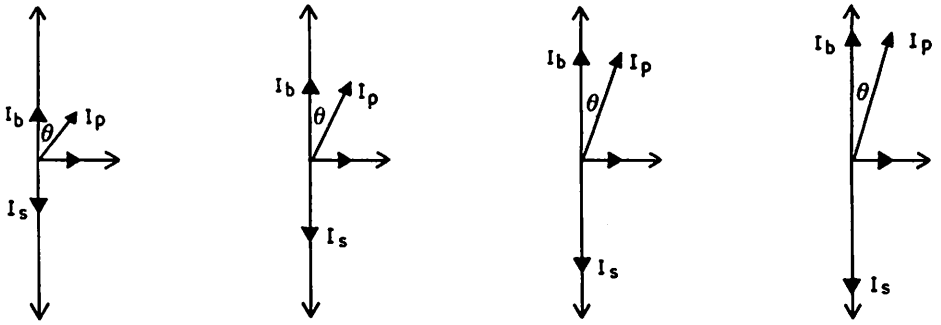


FIG. 2. TRANSFORMER WITH RESISTIVE SECONDARY LOAD.

When the resistance of the secondary load circuit is reduced, the secondary current increases correspondingly. To supply the additional energy, and to counter the demagnetising effect of the increased secondary current, the balance current increases also.

The vector diagrams of Fig. 3 show the effect of connecting progressively lower values of resistor to the secondary winding. When the transformer is fully loaded, (Fig. 3d), the balance current is very much greater than the magnetising current, and, for most practical purposes can be considered as being equal to the total primary current. Under these conditions the primary phase angle is very small, and therefore the primary winding exhibits the resistive characteristics of the secondary load circuit.

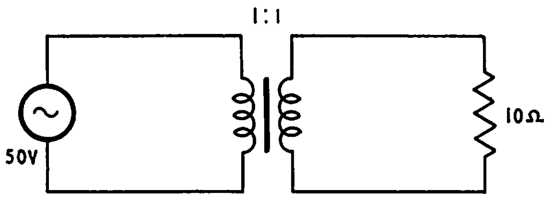


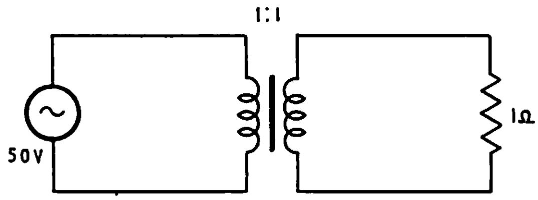
(a) (b) (c) (d)

FIG. 3. TRANSFORMER WITH RESISTIVE SECONDARY LOADS.

When the resistance of the load circuit is so low that the maximum rated secondary current value of the transformer is exceeded, the primary current reaches an abnormally high value. In practical transformers, the windings possess some resistance, and under such overloaded conditions, sufficient heat can be produced within the transformer to cause permanent damage.

Example No. 2. A transformer with an equal number of turns on each winding is connected to an alternating voltage supply of 50 volts. Neglecting the effects of losses and the small magnetising current, calculate the primary current when circuits having resistances of (i) 10 ohms and (ii) 1 ohm are connected to the secondary winding.





As $T = 1$
Secondary Voltage = Primary Voltage.

(i).... Secondary Current $= \frac{E_s}{R_s}$

$= \frac{50}{10} = 5$ Amps

Balance Current $= T \times I_s$

$= 1 \times 5$

$= \underline{5 \text{ Amps}}$

$=$ Primary Current (Approx.)

(ii).... Secondary Current $= \frac{E_s}{R_s}$

$= \frac{50}{1} = 50$ Amps

Balance Current $= T \times I_s$

$= 1 \times 50$

$= \underline{50 \text{ Amps}}$

$=$ Primary Current (Approx.)

Answers = (i) 5 Amps; (ii) 50 Amps.

2.6 Effect of Turns Ratio. Fig. 4a shows a transformer which has a turns ratio of 2, that is, there are twice as many secondary turns as there are primary turns.

When an alternating voltage is applied to the transformer, a magnetising current flows in the primary winding. This current (I_m) lags the applied voltage (E_p) by 90°. In the secondary winding, the induced voltage (E_s) is 180° out of phase with E_p, but, because of the turns ratio, E_s is twice the value of E_p. This is shown in Fig. 4b, which represents the no-load condition.

As a load circuit is connected to the secondary winding, current flows in the secondary circuit. As the load is resistive, the secondary current (I_s) is in phase with E_s (Fig. 4c).

The balance current in the primary winding (I_b) is 180° out of phase with I_s. As the primary winding has only half as many turns as the secondary winding, I_b needs to be twice the value of I_s to achieve balance (Fig. 4c).

In Fig. 4d, the total primary current (I_p) is found from the vector sum of I_b and I_m. It can be seen that the primary current is approximately twice the value of the secondary current.

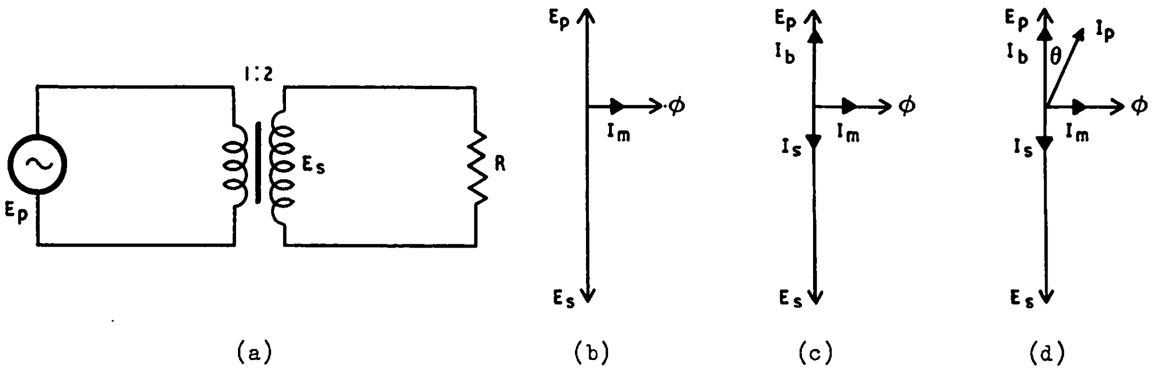
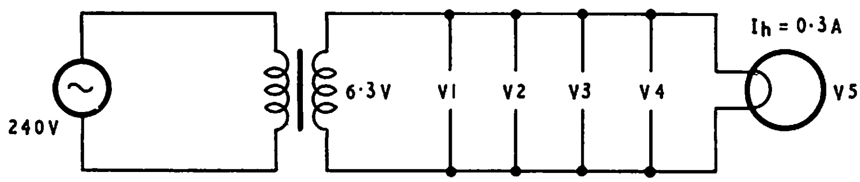


FIG. 4. TRANSFORMER WITH UNEQUAL TURNS RATIO.

Example No. 3. A transformer is used to step down the 240 volt A.C. supply to 6.3 volts for the operation of the heaters of a number of electron tubes, each of which requires a current of 0.3 amps. Neglecting the effects of losses and the magnetising current, find, (i) the turns ratio of the transformer, and (ii) the primary current when five tubes are connected in parallel.



Secondary Current = $I_h \times 5$

= 0.3×5 = 1.5 Amps

(i).... $E_s = T \times E_p$

$\therefore T = \frac{E_s}{E_p}$

$= \frac{6.3}{240} = \frac{1}{38}$ (approx.)

(ii).... Balance Current = $T \times I_s$

$= \frac{1}{38} \times 1.5$

= 0.04 Amps.

= Primary Current (Approx.)

Answers = (i) $\frac{1}{38}$ (ii) 0.04 Amps.

2.7 Transformer with Inductive Secondary Load. Fig. 5a shows a transformer having windings with equal numbers of turns, and with an inductive circuit connected to the secondary winding. It is assumed that the characteristics of the load circuit are such that the secondary current (I_s) lags the secondary voltage (E_s) by approximately 45°.

The operating conditions in the primary winding are shown in the vector diagram (Fig. 5b) which is constructed using the same method as in previous diagrams.

Note that the primary balance current (I_b) is again drawn 180° out of phase with I_s, and that because of the lagging effect of the magnetising current (I_m) the phase difference between I_p and E_p is greater than that between I_s and E_s.

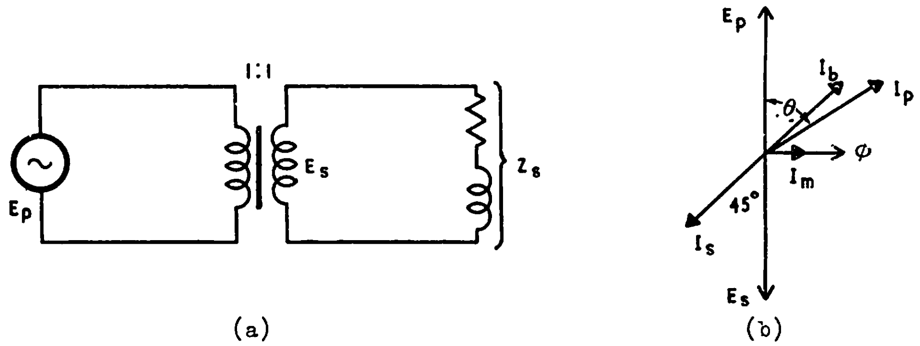


FIG. 5. TRANSFORMER WITH INDUCTIVE LOAD.

Fig. 5b shows that comparatively large currents flow in the windings, but because the secondary load circuit is inductive only a small amount of energy is consumed in the load.

The efficiency of a practical transformer operated under these conditions is comparatively low, as the winding (I^2R) losses are considerable and out of all proportion to the amount of useful energy transferred.

2.8 Transformer with Capacitive Secondary Load. Fig. 6a shows a 1 : 1 transformer with a capacitive load connected to the secondary winding. In the secondary circuit the current (I_s) leads the voltage (E_s) by approximately 45°.

The vector diagram (Fig. 6b) shows that the balance current (I_b) is equal to I_s, and as these currents are 180° out of phase, I_b leads the primary voltage E_p.

The primary current (I_p) is found from the vector sum of I_b and I_m; as I_m lags by 90°, the phase difference in the primary circuit is less than that in the secondary circuit.

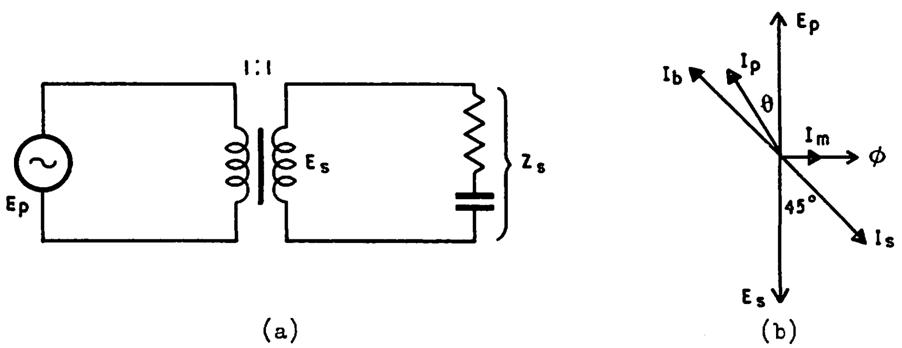


FIG. 6. TRANSFORMER WITH CAPACITIVE LOAD.

In a practical transformer the effect of the losses cause a further reduction in the phase angle in the primary circuit. When the load circuit is only slightly capacitive, the primary current can lag the primary voltage.

Under certain circumstances, the capacitance in the load circuit can combine with the inductance of the transformer to cause a resonant condition, when the secondary voltage under load can exceed the no-load voltage.

2.9 Reflected Impedance. We have seen that when the impedance of the secondary load circuit is changed, the subsequent change in secondary current causes a corresponding change in primary current.

As this change in primary current is fundamentally due to a change in primary impedance, the change in secondary load impedance causes a proportional change in impedance in the primary winding.

This action is commonly called "reflection", and the impedance of the load as "seen" by the energy source through the transformation ratio, is referred to as a reflected impedance.

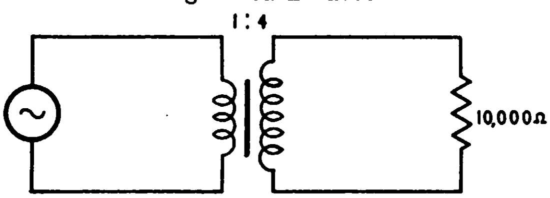
The ratio between the impedance of the load circuit and the reflected primary impedance is called the Impedance Ratio.

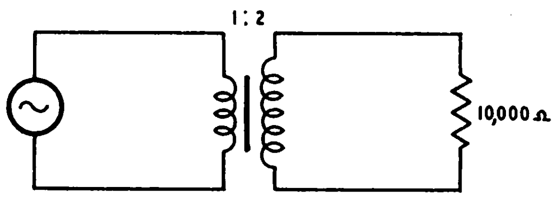
We saw in the paper "Electromagnetic Induction" of Applied Electricity 1, that the impedance ratio of a transformer is equal to the square of the turns ratio, or

$$T^2 = \frac{Z_S}{Z_P}$$

where
T = Turns Ratio
Z_p = Impedance of primary winding
Z_s = Impedance of secondary load circuit.

Example No. 4. Transformers with turns ratios of (i) 4 and (ii) 2 are used in turn to connect a circuit of 10,000 ohms impedance to an alternating voltage source. Neglecting the effects of losses, find the impedance of the transformer primary winding in each case.





(i)....

$$T^2 = \frac{Z_s}{Z_p}$$

$$\therefore \quad Z_p = \frac{Z_s}{T^2} = \frac{10{,}000}{4 \times 4} = \underline{625 \text{ ohms}}$$

(ii)....

$$T^2 = \frac{Z_s}{Z_p}$$

$$\therefore \quad Z_p = \frac{Z_s}{T^2} = \frac{10{,}000}{2 \times 2} = \underline{2{,}500 \text{ ohms}}$$

Answers = (i) 625 ohms; (ii) 2,500 ohms.

In the same way, the transformed impedance of the primary source appears across the secondary winding. However, as we are now "looking" into the transformer in the reverse direction, the turns ratio figure is inverted when calculating the impedance of the secondary winding.

In simple transformer calculations, the effects of the core losses and the resistance of the windings are not considered, and therefore, there is a slight difference between the measured value of impedance and the figure obtained by calculation. However, the discrepancy is not serious and the calculated value is sufficiently accurate for most practical purposes.

2.10 Impedance Matching. In telecom we are concerned with the transmission of A.C.'s over circuits which contain many different items of equipment such as subscribers instruments, lines, amplifiers, etc. As these signal currents are often at very low power levels, electrical energy must be transferred from one circuit to another as efficiently as possible.

We saw in the paper "Electromagnetic Induction" of Applied Electricity 1, that in a D.C. circuit, maximum power transfer takes place when the resistance of the load is equal to the internal resistance of the source. The same conditions apply in resistive A.C. circuits, but where the load and energy source are reactive, maximum power transfer occurs when the resistance of the load equals the resistance of the source, and when the reactances of the load and source are equal in value but opposite in sign. However, these conditions are seldom encountered, and for most practical purposes, the maximum possible power transfer takes place when the impedance of the source equals the impedance of the load.

In telecom very few of the component circuits of a communication channel have equal impedance and, to obtain efficient power transfer, it is necessary to use transformers to connect the various components so that their impedances appear to be equal or are "matched".

2.11 Impedance Matching Using Transformers. We have seen that the impedance of the circuit connected to one winding of a transformer is reflected into the other winding, and that the magnitude of the reflected impedance depends on the turns ratio.

In Example No. 4, a secondary load impedance of 10,000 ohms appears to be 625 ohms when seen from the energy source through a turns ratio of 4. When the turns ratio is 2, the source "sees" the load as an impedance of 2,500 ohms.

Therefore, by using a transformer of suitable turns ratio, it is possible to connect a load to an energy source of unequal impedance, so that

(i) the impedance of the load, as seen by the source, appears equal to the source impedance;

(ii) the impedance of the source, as seen by the load, appears equal to the load impedance.

When this is achieved, the impedances are matched and energy is transferred efficiently from the source to the load.

The turns ratio of a matching transformer can be found from -

$$T^2 = \frac{Z_S}{Z_P}$$

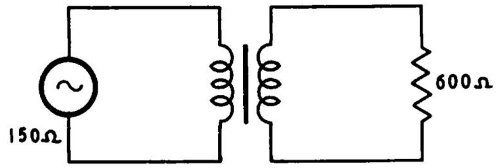
where

T = Turns Ratio

Z_S = Impedance of circuit connected to secondary winding

Z_P = Impedance of circuit connected to primary winding.

Example No. 5. Calculate the turns ratio of a matching transformer suitable for connecting a 600 ohm load circuit to an A.C. source having an internal impedance of 150 ohms.



$$T^2 = \frac{Z_s}{Z_p}.$$

$$\therefore \quad T = \sqrt{\frac{600}{150}} = 2.$$

Answer = 2.

2.12 Transformer Losses. In examining the principles of operation of a transformer, we have considered the transformer as perfect, overlooking the losses which exist in practical transformers.

Briefly these are -

(i) Winding Loss. This is an I^2R loss due to the resistance of the windings. Winding losses increase as the loading increases.

(ii) Eddy Current Loss. This is a power loss caused by the production of eddy currents in the core. This loss remains fairly constant from no-load to full load but it increases rapidly as the frequency of operation rises.

(iii) Hysteresis Loss. This refers to the energy spent in reversing the magnetisation of the core material. Hysteresis losses increase with frequency.

(iv) Magnetic Leakage. This occurs when part of the flux from one winding does not link with the turns of the other winding. Its effect is to add to the inductive reactance of the windings, and so reduce the secondary terminal voltage.

With correct design these losses can be kept to a minimum and modern transformers are very efficient.

As a matter of interest, the efficiency of a transformer is expressed as a percentage and is given by -

$$\text{EFFICIENCY (\%)} = \frac{\text{OUTPUT IN WATTS}}{\text{INPUT IN WATTS}} \times 100$$

2.13 Self-Capacitance. Another factor which has an effect on the operation of a transformer in practice is the self-capacitance which exists across and between its windings. (Fig. 7.)

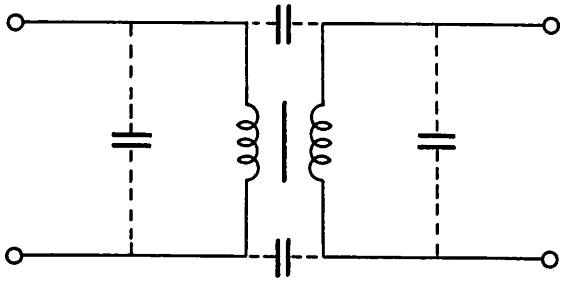


FIG. 7. SELF-CAPACITANCE.

These are due to the combined effects of the minute capacitances between adjacent turns, adjacent layers and adjacent windings.

Although the values of these self-capacitances are comparatively small, they can have a serious shunting effect when the transformer operates at high frequencies. When the transformer operates over a range of frequencies, the self-capacitance can combine with the "leakage reactance" and produce a resonant condition at one frequency within the range. This causes a marked deviation from the normal response of the transformer.

The transformers used in telecom are often required to operate over a range of frequencies, and, as a uniform frequency response is desirable, they must be constructed so that the self-capacitance is kept to a minimum.

3. TRANSFORMER CONSTRUCTION.

3.1 For efficient operation, a transformer should be constructed so that all the flux set up by the primary winding links with the turns of the secondary winding and vice versa. This ideal cannot be completely achieved but, in a well designed transformer, the percentage leakage flux is very small.

Irrespective of its type, a transformer has three essential sections. These are -

(i) The Core.
(ii) The Windings.
(iii) The Shielding.

3.2 Transformer Cores. The core of the transformer provides the path for the operating flux. It should have minimum reluctance consistent with minimum eddy current and hysteresis losses at the operating frequency. Its shape should be such that the windings can be readily accommodated with maximum flux linkage between windings.

For operation at different frequencies, transformer cores are made from different materials.

At power frequencies, audio frequencies and the lower carrier frequencies (up to about 20 kc/s) laminated cores of silicon steel (stalloy) or nickel iron are used.

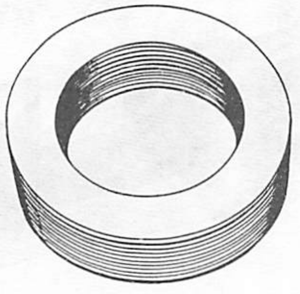
At higher carrier frequencies and radio frequencies, the eddy current losses in a laminated core become excessive and iron dust or "ferrite" cores are used. (Ferrites are a group of ceramic-like magnetic materials in which iron oxide is the major component. These materials have high permeability and extremely high resistivity. As their eddy current losses are negligible, ferrites are suitable for use in solid cores at frequencies up to 100 Mc/s.)

At extremely high radio frequencies efficient operation can only be achieved by using air cores.

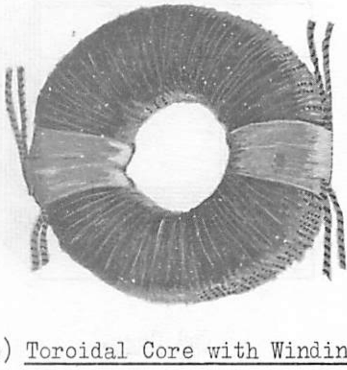
Most solid (ferrite) or laminated cores have a closed magnetic circuit, but where the primary current has a D.C. component, an air gap is left in the core to prevent magnetic saturation.

Of the closed magnetic circuit cores, there are three types in general use. They are -

(i) The Toroidal Type. This type of core is in the shape of a closed ring. (Fig. 8.) The circular form of the core enables the windings to be accurately balanced, that is to have identical electrical characteristics. The leakage flux is negligible as the coils are would over the full length of the core. Although the winding procedure is complicated this type of core is used extensively in telecom.



(a) Toroidal Core.



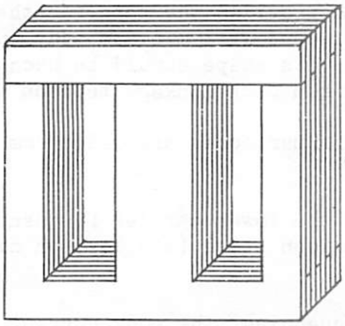
(b) Toroidal Core with Winding.

FIG. 8. TOROIDAL TRANSFORMER CORE.

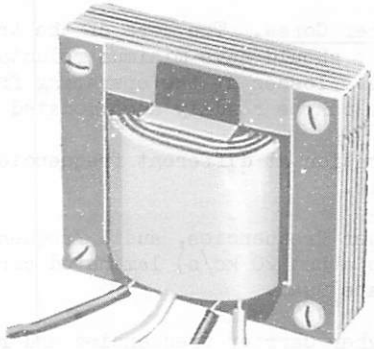
(ii) The Shell Type. In this design, (Fig. 9), the windings are accommodated on the centre limb of the core. The outer limbs form parallel flux paths and therefore have half the cross-sectional area of the centre limb.

The stampings from which a laminated shell core is assembled can be of a variety of shapes, but the "E" and "I" type is the most common. Fig. 9a represents a shell type laminated core in which the joints between the "E" and "I" sections are interleaved to prevent the formation of an air gap.

This type of construction forms an efficient magnetic circuit, and is used extensively in transformer construction.



(a) Shell Core.



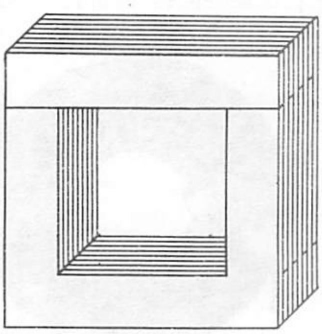
(b) Shell Core with Windings.

FIG. 9. SHELL TYPE TRANSFORMER CORE.

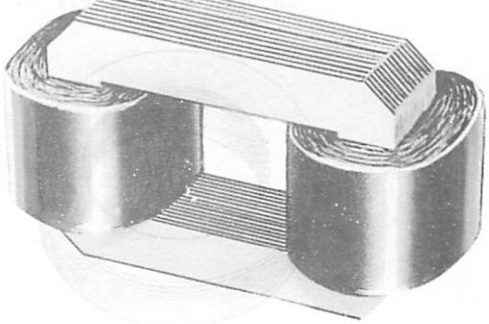
(iii) The Core Type. Fig. 10 shows a transformer core of this design in which the magnetic circuit takes the form of a hollow square. This core is often built up from "U" and "I" type laminations, which can be interleaved as in Fig. 10a.

The windings can be placed on opposite limbs for high voltage isolation, or, the windings can be split with half of each winding placed on each limb. This latter method reduces induction from stray magnetic fields as the interfering e.m.f.'s induced in each half of each winding are in opposition and they neutralise each other when the windings are accurately divided.

The use of this core is generally restricted to transformers in which low noise level is important such as amplifier input transformers, or where high voltages are involved as in T.V. line output transformers.



(a) Core.



(b) Core with Windings.

FIG. 10. CORE TYPE TRANSFORMER CORES.

3.3 Transformer Windings. The number of windings provided is determined by the application of the transformer. Many transformers have two or more secondary windings and each winding may be "tapped" to provide a number of outputs. The number of turns on each winding is influenced by factors such as the operating frequency, the desired voltage or impedance of the windings and the size and composition of the core.

The windings are usually wound on a former and assembled to the core as a unit. They can be layer wound, that is, the turns are wound in layers over the full length of the winding space, or they can be wound in sections or "pies" which are placed side by side along the core. This latter method is used to minimise the self-capacitance of the winding.

3.4 Shielding. In order to reduce interference and noise in communication circuits, transformers must be provided with electromagnetic and electrostatic shields.

Electromagnetic shields are necessary to confine the flux to the transformer and prevent electromagnetic induction into and from neighbouring circuits.

Low frequency transformers are usually enclosed in a cover or case of magnetic material which acts as a magnetic short circuit, preventing the flux from extending beyond the shield.

In high frequency transformers, shielding is achieved by enclosing the transformer in a copper or aluminium can. The flux from the transformer induces eddy currents in the can. The eddy current flux opposes the transformer flux and prevents it from spreading outside the shield.

Electrostatic shields are provided to prevent electrostatic coupling.

Transformers require two types of electrostatic shielding:-

(i) An External shield to prevent the electric field from the transformer from causing interference in neighbouring circuits and vice versa. This form of shielding may be provided by the same earthed metallic can which is used for electromagnetic shielding.

(ii) An Internal shield to reduce the capacitance between windings. Shielding is achieved by separating the windings with an earth connected non-magnetic foil wrapping, usually copper. The joint in the foil must be insulated to prevent the formation of a short-circuited turn (Fig. 11).

By this means, the capacity between windings is replaced by capacity between each winding and earth. In the event of an insulation breakdown in a power transformer the electrostatic shield prevents a direct connection between high voltage and low voltage windings.

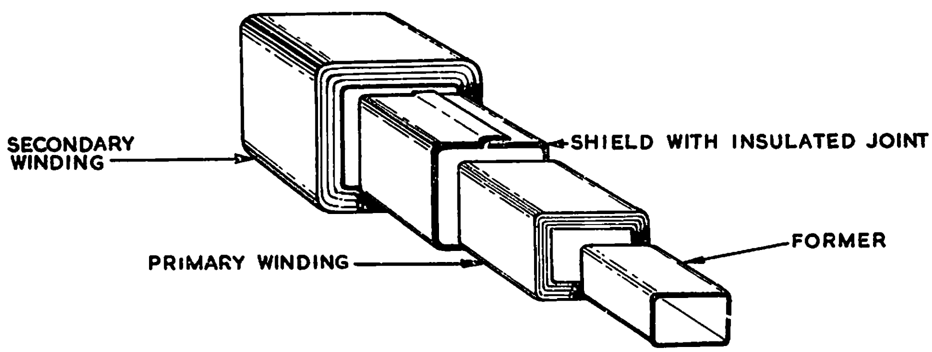


FIG. 11. SHIELDED WINDINGS.

4. TYPES OF TRANSFORMERS.

4.1 The transformers used in telecom equipment vary in size, shape and general construction according to the application of each type, but they can be broadly classified according to their operating frequency as -

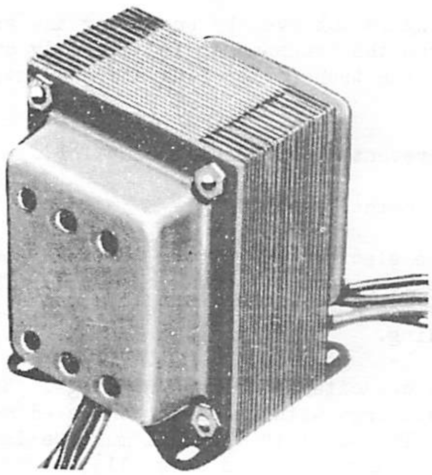
(i) Power transformers.

(ii) Audio frequency transformers.

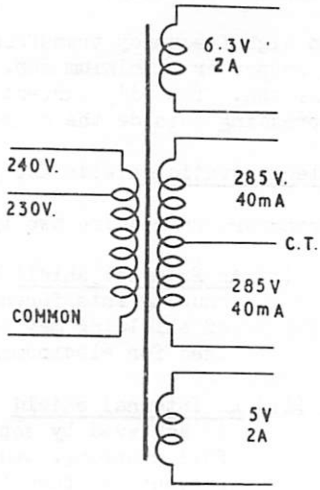
(iii) Radio frequency transformers.

4.2 Power Transformers are designed to operate at the power frequency (50 c/s), and are used to step up or step down the mains supply voltage to a desired value.

The majority of power transformers have closed magnetic circuits employing shell or core type laminated iron cores. Power transformers often have two or more secondary windings each with a different number of turns to provide different voltage outputs. A typical small power transformer as used in mains operated electronic equipment is shown in Fig. 12.



(a) Power Transformer.



(b) Arrangement of Windings.

FIG. 12. POWER TRANSFORMER.

When a power transformer is under load, the secondary terminal voltage is always slightly less than the no-load voltage. This reduction in secondary voltage is mainly due to the voltage drop in the resistance of the windings.

The difference between the no-load voltage and the full load voltage is known as the Regulation of the transformer, and it is usually expressed as a percentage of the no-load voltage.

$$\text{Regulation } (\%) = \frac{\text{No-Load Secondary Voltage} - \text{Full Load Secondary Voltage}}{\text{No-Load Secondary Voltage}} \times 100$$

In a well designed transformer, the regulation does not exceed 5%.

The power output available from a transformer is governed by the cross-sectional area of the core. For example, a transformer with twice the power output of another needs to have a core with a cross-sectional area approximately $\sqrt{2}$ times greater than that of the smaller transformer.

Small radio type power transformers (Fig. 12) are rated in terms of maximum secondary current. A transformer rated at "100 mA" could be permanently damaged if the secondary current exceeded 100 mA for a sustained period.

Larger power transformers are rated in terms of secondary volt-amps. The output is not expressed in watts as the secondary load circuit may not be completely resistive.

4.3 Audio Frequency Transformers operate at frequencies in the audio range and are used to transfer or couple a signal from one circuit to another, to electrically isolate two circuits or to match circuits of different impedance.

These transformers usually have laminated iron cores which can be of the open or closed magnetic circuit type. The windings are wound with fine wire, and often special winding methods are used to reduce the self-capacitance to give a uniform or "flat" response over the frequency range.

Audio Frequency transformers require effective shielding to prevent the introduction of noises such as clicks and power hum into the circuit. This is particularly important where the signal current has a low power level.

The transformer shown in Fig. 13 is a matching transformer designed to operate over the frequency range 30 c/s to 12 kc/s.

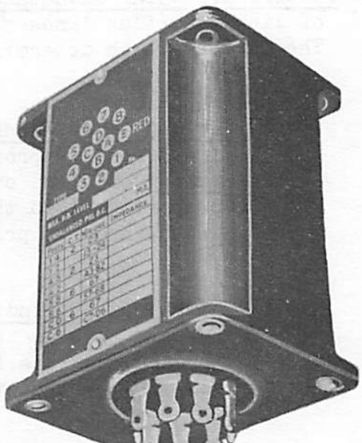


FIG. 13. AUDIO FREQUENCY TRANSFORMER.

4.4 Radio Frequency Transformers are used to couple circuits operating at radio frequencies or to step up or step down radio frequency voltages.

In most cases, the windings are loosely coupled magnetically, and ferrite, iron dust or air cores are used. Shielding is achieved by enclosing the unit in a can of aluminium or other low resistance metal.

Many R.F. transformers have a capacitor connected in parallel with one or both windings to form resonant circuits. When signals at different frequencies are applied to the primary winding of such a "tuned" transformer, those signals at or near the resonant frequency predominate in the secondary circuit. A typical tuned radio frequency transformer is shown in Fig. 14.

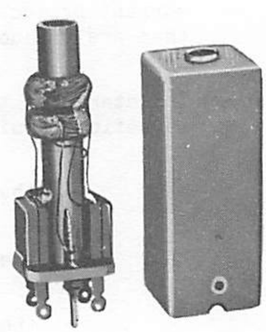


FIG. 14. RADIO FREQUENCY TRANSFORMER.

4.5 Because of the wide variety of transformers used in carrier systems, and the extent of the carrier frequency range, no specific reference to "carrier frequency transformers" has been made in this paper. However, these transformers mainly perform the same basic functions of coupling, isolating and impedance matching and are constructed according to the requirements of their operating frequency.

5. INDUCTORS.

5.1 An inductor is a device which has been specifically constructed so that it possesses a certain value of inductance.

In its simplest form an inductor consists of a number of turns of wire. The winding is arranged so that the flux set up by the passage of varying or alternating current links the turns and induces an e.m.f. which opposes the change in current.

5.2 Factors Affecting Inductance. The inductance of an inductor can be expressed in terms of linkages (flux lines x turns) created when the current changes at a certain rate. The factors which determine the inductance are -

(i) The Number of Turns. The number of linkages produced by a certain change in current is proportional to the resultant change in flux and to the number of turns on the coil. But as the change in flux is also proportional to the number of turns, the linkages (and therefore the inductance) is proportional to the number of turns squared.

(ii) The Method of Winding. Inductance is also affected by the method of winding. Factors such as the spacing between turns, the number of layers in the winding, and the type of winding procedure adopted, all influence the coupling between the turns and consequently affect the inductance.

(iii) The Reluctance of the Magnetic Circuit. The reluctance of a magnetic circuit is the opposition it offers to the establishment of a magnetic field. When the current flowing in the winding of an inductor changes, the extent of the resultant change in flux depends on the reluctance of its magnetic circuit.

When two inductors have an equal number of turns and when the magnetic circuit of one has half the reluctance of the other, a certain change in current produces twice as many linkages in the low reluctance inductor than are produced in the inductor having the greater reluctance.

Inductance is therefore inversely proportional to the reluctance of the magnetic circuit, which is the combined effect of -

- the cross-sectional area of the core;
- the length of the core;
- the permeability of the core under working conditions.

With air cored inductors, inductance is independent of current, as the permeability of air is unity and does not change.

With iron cored inductors however, the permeability of the iron varies with the magnitude of the magnetising force produced by the current. All iron cored inductors therefore, are rated as possessing a certain inductance at a specified value of current.

5.3 Construction. Like a transformer, an inductor has three main parts -

(i) The Core.

(ii) The Winding.

(iii) The Shielding.

(i) The Core. Cores used for inductors follow much the same pattern as those used in transformers which operate within the same frequency range.

For different applications, inductor cores can be of the open magnetic circuit type, or of the closed magnetic circuit type with or without an air gap. The material used in the core depends on the operating frequency, but laminated iron, ferrite or air cores are the most common.

Laminated cores can be of the toroidal, shell or core design, but a much wider variety of shapes is available in moulded ferrite cores. These include rods (cylindrical or threaded), tubes, slabs and pot cores. The make-up of one type of pot core is shown in Fig. 15.

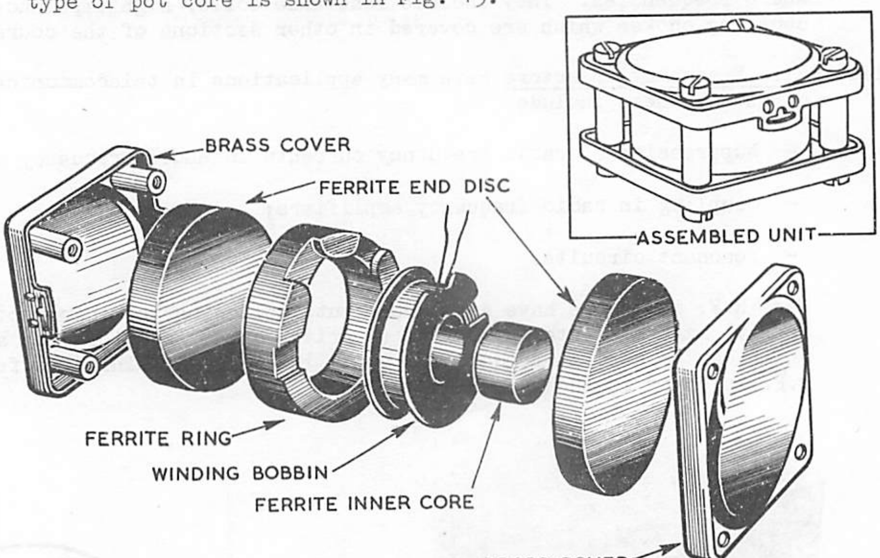


FIG. 15. FERRITE POT CORE INDUCTOR.

(ii) Windings. Inductors operating at low frequencies are usually layer wound over the length of the available winding space. For operation at higher frequencies, the self-capacitance of a layer winding is excessive, and special winding methods are adopted. To reduce skin effect, these inductors are wound with Litzendraht (Litz) wire which consists of a number of individually insulated interwoven strands or, where large current values are involved, the inductor is wound in copper tubing.

(iii) Shielding. Inductors require electromagnetic and electrostatic shields, and these are provided by enclosing the core and winding in an earthed metal case.

When the inductor operates at low frequencies, the case is made from a magnetic material, but for high frequency operation, the unit is enclosed in a case made from a good electrical conductor such as aluminium.

5.4 Types of Inductors. There are many different types of inductors used in telecommunication circuits, and it is not possible to give details of the construction and application of all types at this stage. However, most inductors come within the scope of one of the following classifications.

(i) Power Inductors or choke coils are designed for low frequency operation in association with power equipment. In telecom, they are mainly used in smoothing filters in rectifier power supplies. Most power chokes have laminated iron cores of the shell or core type. In most applications, the greater part of the current is D.C. and an air gap must be left in the magnetic circuit. Most power chokes are rated in inductance with reference to a certain current.

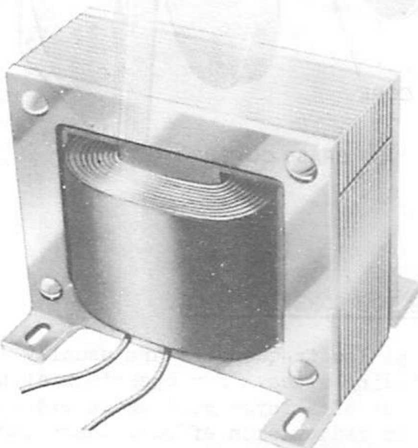
For example, one type of choke is rated at 3 henries when it is carrying its rated current of 300 milliamps (D.C.). When the current is reduced to 200 milliamps, the inductance increases to 4 henries. A typical power choke is shown in Fig. 16a.

(ii) Audio Frequency Inductors are designed to offer high impedance to currents at audio frequencies. They include reactance coils, high impedance relays and coupling chokes which are covered in other sections of the course.

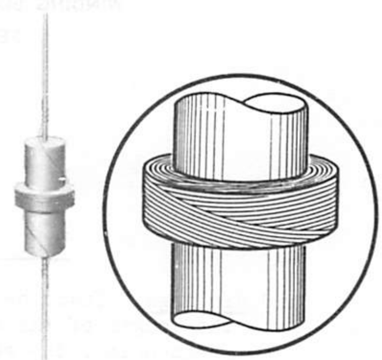
(iii) Radio Frequency Inductors have many applications in telecommunication circuits; these include

- suppression of radio frequency currents in audio frequency circuits;
- coupling in radio frequency amplifiers;
- resonant circuits.

Many R.F. inductors have air cores, but, following the introduction of the ferrite magnetic materials, iron (ferrite) cored inductors are available which can be used at frequencies up to 100 Mc/s. A miniature ferrite cored R.F. inductor is shown in Fig. 16b.



(a) Low Frequency Inductor.



(b) Radio Frequency Inductor.

FIG. 16. TELECOMMUNICATION INDUCTORS.

Sometimes an inductor has auxiliary windings or additional features to enable it to perform special functions. As the operation of these types requires an understanding of the equipment with which they are associated, they are described in other papers of the course.

NOTES

6. TEST QUESTIONS.

1. Briefly describe the principle of operation of a transformer.

2. A transformer has 1200 turns on the primary winding and 3000 turns on the secondary winding. Find the secondary voltage when an alternating voltage of 240 volts is applied to the primary winding.

3. Draw a simple vector diagram to illustrate the no-load condition of a transformer having a turns ratio of 1.

4. When a resistive load circuit is connected to the secondary winding, the primary current rises above / remains the same as / falls below the no-load value, because ....

5. Define Balance current. What relationship exists between balance current and secondary current in terms of magnitude and phase?

6. A transformer is used to operate four 50 volt 100 watt soldering irons from the 240 volt supply. Neglecting losses, find
   (i) the turns ratio;
   (ii) the secondary current;
   (iii) the primary current.

7. What is meant by reflected impedance?

8. A transformer with 600 primary turns and 1,200 secondary turns has a circuit of 800 ohms impedance connected to the secondary winding. Ignoring losses, what would the impedance of the primary winding be under these conditions?

9. What is meant by impedance matching?

10. A 2 ohm loudspeaker is to be connected to an amplifier having an output impedance of approximately 10,000 ohms. What would be the turns ratio of a suitable matching transformer?

11. Describe three types of closed circuit transformer cores in common use.

12. Name three materials used for transformer cores and briefly state where each is used.

13. Why are transformers provided with electromagnetic shields?

14. Transformers often have internal and external electrostatic shields.
    (i) The internal shield consists of ....
    and its purpose is to ....
    (ii) The external shield consists of ....
    and its purpose is to ....

15. For what purpose are power transformers used?

16. What is meant by the "regulation" of a power transformer?

17. For what purpose are audio frequency transformers used?

18. Briefly describe the construction of a radio frequency transformer.

19. Name the factors which influence the inductance of an inductor.

20. Why is an air gap left in the core of a power choke?

END OF PAPER.